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Contemporary Trends in Human Factors and Ergonomics within Engineering Research

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Abstract: This review explores human factors and ergonomics (HFE) in the engineering subject areas and analyzes research over the last five years across physical, cognitive, and organizational ergonomics and is associated with the Industrial Revolution era. This review aims to identify existing trends in HFE research related to the Industrial Revolution. This study used a systematic four-step methodology and drew from the Science Direct and Scopus databases. The methodology involves conducting a careful literature search, selecting pertinent and suitable literature references, conducting bibliometric analysis, and participating in qualitative discussions. A total of 353 articles are identified for further analysis. Our findings indicate that the current state of Human Factors and Ergonomics (HFE) research remains largely situated within the research paradigm of the Industrial Revolution 3.0 era. Investigations oriented towards the Industrial Revolution 4.0, such as integrating machine learning and artificial intelligence into physical, cognitive, and organizational ergonomics, are still limited. The insufficient adoption of these advancements underscores the necessity for ongoing development of HFE research to leverage these advancements in order to align with the trajectory towards Industry 4.0.

Keywords: Human factors, ergonomics, physical ergonomics, cognitive ergonomics, organizational ergonomics.

Introduction

The human factors and ergonomics (HFE) discipline is characterized as a science field that focuses on understanding the interaction between humans and various components of a system. It utilizes theoretical principles, data, and methodologies to enhance well-being and performance [1], [2]. The primary objective is to optimize the effectiveness and efficiency of tasks and various activities to achieve well-being and performance goals, including safety, fatigue and stress reduction, and improved quality of life [3], [4]. HFE encompasses three specific main domains: physical ergonomics, cognitive ergonomics, and organizational ergonomics [5], [6].

Physical ergonomics is related to biomechanical activities and body posture. This domain includes ergonomic considerations for biomechanics, work posture, material handling, repetitive motion, work-related musculo-skeletal disorders, and other factors related to safety and health [7], [8], [9]. Various methods and measurement tools have been used in previous research related to risk assessment, such as RULA, OWAS, and REBA [10], [11], [12], [13]. However, most of these methods required manual data collection, involving direct observation of operators during specific tasks [14], [15]. In the Fourth Industrial Revolution, incorporating machine learning technology has the potential to automate the data collection and processing stages, offering significant advantages in terms of time efficiency, cost-effectiveness, and accurate results [16], [17], [18].

Cognitive ergonomics primarily involves the cognitive processes to facilitate human interaction with systems while considering human competence and environmental factors [19]. Areas of study include issues related to mental workload using technologies such as eye-tracking [20], [21], a game-based approach [22], [23], and visual interaction [24], [25]. Factors like humidity, temperature, air quality [26], heart rate variability [27], and human-robot interaction [28], [29] could impact cognitive responses to workplace features and conditions. Research interest in this ergonomics domain is growing due to the widespread use of information systems that can contribute to the cognitive workload of operators. Consequently, most investigations focus on ensuring compliance with regulatory requirements, often neglecting the well-being of operators. Previous research has concentrated on tools for assessing mental workloads, such as the NASA Task Load Index, and Rating Scale

Mental Effort [30], [31], [32], and the classification of mental fatigue using Electroencephalogram (EEG) sensors [33].

Organizational ergonomics focuses on optimizing socio-technical systems, including structural attributes, policies, work environment, organizational processes, worker ergonomic awareness, and participative culture [34], [35], [36]. Planning and organization, particularly in production processes, are largely influenced by the knowledge, abilities, and physical and psychological well-being of the workforce to reduce stress, enhance motivation, and improve employee satisfaction[37], [38].

In addition, all three domains require studies of interaction and collaboration. From physical workload to cognitive demands and organizational structures, Industry 4.0 reshapes the human experience in work systems through both theoretical and practical applications [39], [40]. Furthermore, humans, as cohesive entities both physically and mentally, cannot be separated [41], [42]. Although individuals are responsible for solving their problems, they often require assistance from other resources, including technology, that are skilled in organization and experience [43]. Moreover, jobs characterized by excessive physical demands or prolonged sitting are also considered hazardous [44].

Previous studies have not comprehensively addressed the trends in Human Factors and Ergonomics (HFE) research in tandem with the developments of the Industrial Revolution. This review is crucial for contextualizing the state of HFE research within the current industrial revolution shift. Therefore, this review aims to identify existing trends in HFE research related to the Industrial Revolution. The subsequent sections are structured as follows: section two outlines the proposed methodology, section three contains results and discussions regarding the findings and future research, and section four summarizes the conclusions.

Methods

To attain the main goals, this study utilizes a thorough four-step methodology for an extensive literature review. The process involves: (1) conducting a literature search from scientific database; (2) selecting pertinent and suitable literature references; (3) conducting bibliometric analysis; and (4) participating in qualitative discussions. Detailed explanations for each step can be found in the subsequent sections. The methodological framework for this study is shown in Figure 1.

Literature Search

The initial phase of this research involves a systematic exploration of the Science Direct and Scopus databases through a methodical literature search. In this review, four principal keywords, specifically "physical ergonomics," "cognitive ergonomics," "organizational ergonomics," and "socio-technical ergonomics," serve as the basis for the search in both databases. This is conducted to retrieve literature records related to published articles in the domain of human factors and ergonomics. The literature search is carried out based on "title articles/abstract/keywords" to identify pertinent literature records. The selection of these two databases is predicated on their accuracy, comprehensive coverage, and prompt indexing process, complemented by integration with other databases [45]. The search duration covers literature records from the last five years, starting from 2019. Therefore, the complete search string for the Science Direct database is as follows: "(physical OR cognitive OR organizational OR socio-technical) AND ergonomics". Subsequently, the search years are restricted to 2019-2023. As for the complete string for the Scopus database, it is as follows: "TITLE-ABS-KEY ((physical OR cognitive OR organization OR socio-technical) AND ergonomics) AND PUBYEAR > 2018 AND PUBYEAR < 2024". In this initial search phase, the Science Direct and Scopus databases yielded a total of 354 and 3,761 literature records, respectively, including articles, book chapters, reviews, and proceedings.

Literature Selection

The second stage of this review involves a meticulous selection of relevant articles using specific criteria. For the Science Direct database, the first step is to focus on literature records of research articles only, excluding references related to book chapters and reviews intentionally. This resulted in a total of 281 articles, with 73 literature records excluded. Secondly, the criteria for selecting research articles are restricted to the engineering subject area, resulting in 159 articles, with 122 literature records excluded. The next step involves a comprehensive review in which the authors systematically filter these 159 articles based on their titles, abstracts, and keywords to determine their relevance to the main topic of this literature review. During this screening process, articles are excluded if their content is not explicitly related to physical, cognitive, and/or

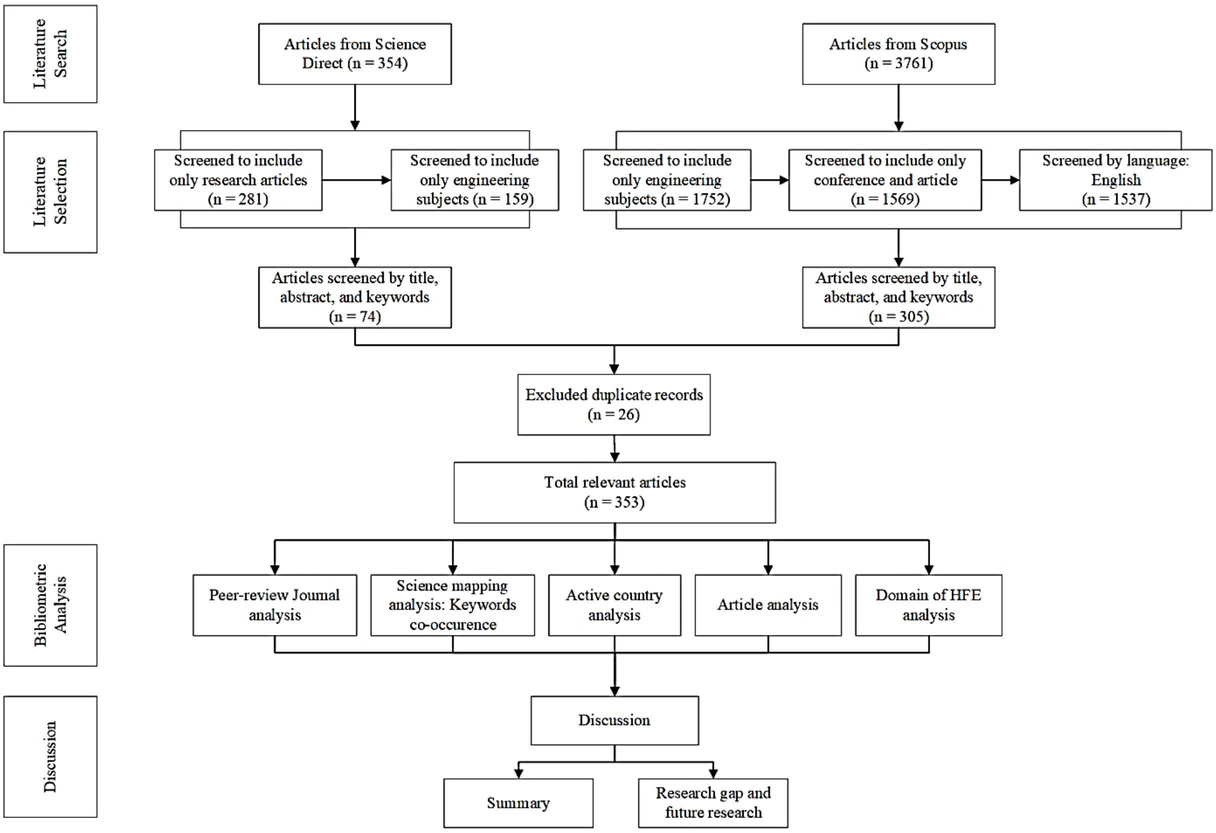

Figure 1. Outline of literature review methods

organizational ergonomics in the industry or engineering scopes. For example, Barton *et al.* (2023) suggested creating home personas to communicate fundamental aspects of the home environment to individuals responsible for designing technology and interventions tailored to it. As a result, 85 articles are excluded, leaving a total of 74 articles for further analysis and inclusion in Mendeley Reference Manager version 2.80.1 as of October 30, 2023.

In the Scopus database, the initial step involves refining the literature records obtained from the search to focus solely on the engineering subject area, resulting in 1,752 articles, with 2,009 literature records excluded. The second step entails filtering literature records exclusively for conferences and articles, yielding 1,569 literature records. Subsequently, in the third step, the literature records are restricted to English articles, resulting in 1,537 literature records. The subsequent step involves further filtering based on pertinent titles, abstracts, and keywords related to the main topic discussed in this literature review. Consequently, 305 articles are identified for subsequent analysis and inclusion in Mendeley Reference Manager version 2.80.1, as of December 1, 2023. Additionally, the relevant articles selected from both Science Direct and Scopus are amalgamated, and potential duplicate articles are scrutinized. A total of 26 duplicate articles from both databases are removed from Mendeley Reference Manager. Following the exclusion of these items, 353 pertinent articles are subjected to bibliometric analysis

Bibliometric Analysis

In the third phase, bibliometric analysis is employed to investigate the relevant articles for further discussion. Five analyses are discussed in this literature review, including peer-reviewed journal analysis, science mapping analysis, active contributing country analysis, article analysis, and Human Factors and Ergonomics (HFE) domain analysis.

Firstly, peer-reviewed journal analysis is conducted by ranking based on the number of relevant articles. The top five peer-reviewed journals are analyzed concerning the dominant HFE domain discussed in those articles. Secondly, science mapping analysis refers to bibliometric analysis techniques. Bibliometric analysis, although primarily focused on literature, possesses the capacity to evaluate research networks and delineate the current scientific knowledge and its evolution based on bibliographies. Various science mapping tools, including

BibExcel, Gephi, CiteSpace, and VOSviewer, are available for bibliometric network analysis and visualization in science research [46], [47]. For this study, VOSviewer version 1.6.19 was chosen due to its availability as a free visualization tool and user-friendly nature for network mapping analysis [48]. The VOSviewer for science mapping, scientometric analysis, and visualization is operated based on keyword co-occurrence.

Thirdly, the analysis of actively contributing countries entails a ranking determined by the number of pertinent articles originating from the respective countries of the authors. This process also involves scrutinizing the predominant domain of Human Factors and Ergonomics (HFE) discussed in the top five countries. In the fourth step, the analysis of articles involves ranking them based on the number of citations received. Subsequently, the top five articles are subject to further discussion. Lastly, the analysis of HFE domains encompasses the examination of all articles (353 articles) with a focus on the HFE domain discussed in the research. These articles are then categorized according to the prevalent domains, which include physical ergonomics, cognitive ergonomics, organizational ergonomics, and the combinations of the domains.

Discussion

The final phase involves a qualitative discussion aimed at providing a comprehensive evaluation of the scientific contributions to physical, cognitive, and organizational ergonomics. This discussion requires a deep exploration of the research gaps identified in this study and serves as a basis for potential further studies in human factors and ergonomics.

Results and Discussions

Peer-reviewed Journal Analysis

The literature selection, as discussed in section 2.2, is used to identify relevant articles published in peer-reviewed journals. Table 1 shows the ranking of peer-reviewed journals with relevant articles on the main topic discussed during the research period based on the number of articles. As shown in Table 1, the analysis reveals the identification of the top 19 peer-reviewed journals, encompassing 74.79% of all peer-reviewed journals. The remaining journals each contribute a smaller number of articles, each containing fewer than four.

Based on Table 1, the top five peer-reviewed journals by the number of articles include Advances in Intelligent Systems and Computing, Applied Ergonomics, International Journal of Industrial Ergonomics, International Journal of Occupational Safety and Ergonomics, and Human Factors and Ergonomics in Manufacturing. Among these 19 peer-reviewed journals, the highest number of articles is published in Advances in Intelligent Systems and Computing, totaling 63 articles (18.48%). Applied Ergonomics is the peer-reviewed journal with the highest number of citations (1,020 articles). However, Automation in Construction has the highest average number of references (36.60 times).

The dominant HFE domain discussed in Advances in Intelligent Systems and Computing is physical ergonomics (46.03%), followed by cognitive ergonomics (20.63%), organizational ergonomics (15.87%), the combination of physical and cognitive ergonomics (7.94%), and the combination of all three domains (1.59%). These results are consistent with the dominant HFE domains in Applied Ergonomics (47.27%), International Journal of Industrial Ergonomics (48%), and International Journal of Occupational Safety and Ergonomics (57.14%). Meanwhile, research in physical, cognitive, and organizational ergonomics equally contributes 25% respectively to Human Factors and Ergonomics in Manufacturing.

Science-mapping Analysis

Science mapping analysis utilizes keyword co-occurrence to construct and map networks of recent research trends relevant to the topic. By employing "co-occurrence" as the type of analysis, "keywords" as the unit of analysis, and "full counting" as the counting method in VOSviewer, with the minimum keyword occurrence set to 5 times, only 28 out of a total of 1,042 keywords meet this threshold. The threshold selection is based on VOSviewer recommendations and several experiments with other parameters to achieve an optimal cluster count. Further investigation is carried out on some keywords with similar meanings by excluding redundant keywords from the mapping, including (1) "mental workload," (2) "work-related musculoskeletal disorders," (3) "physical workload," (4) “cognitive workload,” and (5) "human-robot collaboration." Ultimately, the analysis results in 23 keywords, 6 clusters, 63 links, and a total link strength of 131, as illustrated in Figure 2.

Table 1. List of peer-reviewed journals with relevant articles

No	Journal name	Number of relevant articles	% Total publications	Total citation	Average citation
1	Advances in Intelligent Systems and Computing	63	17.85%	180	2.86
2	Applied Ergonomics	55	15.58%	1020	18.55
3	International Journal of Industrial Ergonomics	25	7.08%	351	14.04
4	International Journal of Occupational Safety and Ergonomics	21	5.95%	141	6.71
5	Human Factors and Ergonomics in Manufacturing	16	4.53%	81	5.06
6	Lecture Notes in Networks and Systems	12	3.40%	27	2.25
7	Safety Science	11	3.12%	146	13.27
8	Robotics and Computer-Integrated Manufacturing	8	2.27%	279	34.88
9	Procedia CIRP	7	1.98%	58	8.29
10	IOP Conference Series: Materials Science and Engineering	6	1.70%	25	4.17
11	Procedia Manufacturing	6	1.70%	41	6.83
12	Lecture Notes in Mechanical Engineering	5	1.42%	2	0.40
13	Automation in Construction	5	1.42%	183	36.60
14	Advances in Transdisciplinary Engineering	4	1.13%	5	1.25
15	Applied Sciences (Switzerland)	4	1.13%	75	18.75
16	Computers & Industrial Engineering	4	1.13%	110	27.50
17	International Journal on Interactive Design and Manufacturing	4	1.13%	30	7.50
18	Journal of Construction Engineering and Management	4	1.13%	53	13.25
19	Sensors (Switzerland)	4	1.13%	91	22.75

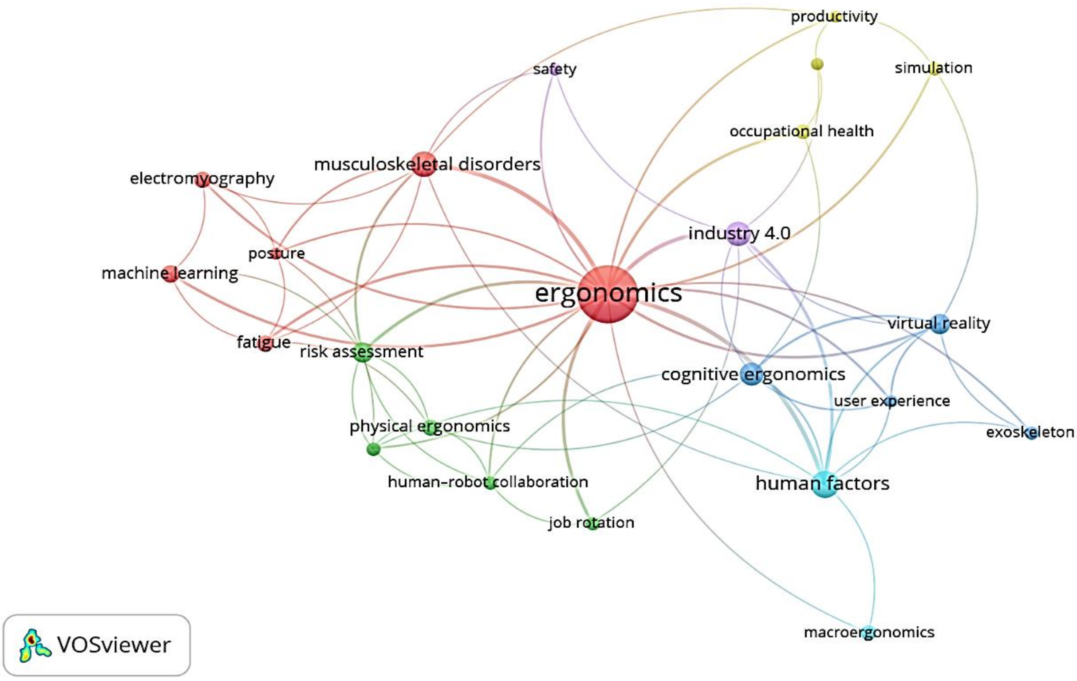

Figure 2. Science-mapping using VOSviewer

Based on Figure 2, keywords such as "ergonomics," and "human factors" have larger font sizes, indicating their higher frequency of use in previous research. The distances and connecting lines in Figure 2 illustrate the relationships between these keywords. For instance, the keyword "ergonomics" is closely associated with "industry 4.0," illustrated by a shorter distance and thicker line. Based on the color differences illustrated, keywords can be categorized into six main keyword groups representing the primary knowledge domains related to the main HFE domain.

Table 2. List of relevant keywords

No.	Keyword	Occurrences	Links	Total link strength	Average pub. year	Cluster
1	Ergonomics	98	19	74	2020	1
2	Musculoskeletal disorders	19	8	19	2020	1
3	Machine learning	9	4	7	2021	1
4	Electromyography	8	4	6	2021	1
5	Fatigue	8	5	8	2021	1
6	Posture	5	5	7	2019	1
7	Risk assessment	12	6	12	2020	2
8	Physical ergonomics	8	5	5	2021	2
9	Manufacturing	6	6	7	2020	2
10	Human-robot collaboration	6	6	7	2021	2
11	Job rotation	6	3	7	2021	2
12	Cognitive ergonomics	16	7	11	2021	3
13	Virtual reality	12	7	14	2020	3
14	Exoskeleton	6	3	4	2020	3
15	User experience	5	4	8	2020	3
16	Occupational health	7	3	6	2019	4
17	Simulation	6	3	5	2020	4
18	Participatory ergonomics	5	3	3	2019	4
19	Productivity	5	4	5	2021	4
20	Industry 4.0	18	7	18	2020	5
21	Safety	5	3	4	2020	5
22	Human factors	22	9	23	2020	6
23	Macroergonomics	7	2	2	2021	6

Table 2 shows the occurrences of keywords and the strength of each node. As shown in Table 2, "ergonomics" and "human factors" are the two most frequently used keywords among the listed terms, indicating that these keywords have been extensively researched in the HFE domain, and follow the clusters and total link strengths. For instance, the total link strength of "ergonomics" is 74, indicating a strong connection between "ergonomics" and "musculoskeletal disorders." Similarly, the total link strength of "human factors" indicates a strong association with "industry 4.0".

There are six keywords in cluster one, including: "ergonomics," "musculoskeletal disorders," "machine learning," "electromyography," "fatigue," and "posture." Musculoskeletal disorders can arise due to various contributing factors, such as a high body mass index (BMI), long working hours, lack of exercise, awkward body posture, high job demands, and workplaces [11], [14], [49]. The effective use of machine learning techniques allows the detection of muscle fatigue based on electromyography (EMG) signals [17], [18], [50]. Not only physically, but a decrease in critical fusion frequency over a specific period also indicates an increase in visual fatigue and mental workload on workers in completing their tasks [24], [51].

In cluster two, the keywords include "risk assessment," "physical ergonomics," "manufacturing," "human-robot collaboration," and "job rotation." The formation of interconnected work environments, motion sequencing, and the enhancement of the physical, sensory, and cognitive capabilities of operators are three technologies that can be effectively used to substantially improve ergonomic conditions and safety in the workplace [52]. Minimizing operational costs on assembly lines and reducing energy load variation among workers can be achieved through job rotation [53], [54]. However, according to Comper *et al.* (2021), high compliance with job rotation does not have a positive effect on musculoskeletal symptoms, work exposure, and workers' performance [55].

The keywords "cognitive ergonomics," "virtual reality," " exoskeleton," and "user experience" are in cluster three. Virtual Reality (VR) technology has garnered increased interest and can be used to enhance task performance while avoiding excessive stress and mental workload [56]. Combining user experience (UX) based technology with tools for analyzing human data aids in designing or restructuring complex industrial systems centered around human interaction [57], [58], [59].

Furthermore, the keywords "occupational health," "simulation," "participatory ergonomics," and "productivity" are in cluster four. The use of participatory design to highlight various aspects of work and stimulate discussions on workplace safety can serve as criteria and guiding principles in the operation and evaluation [60], [61], [62]. In the context of industrial production and productivity, ergonomics simulation enables companies to discover and implement optimal solutions that prioritize profitability, output, quality, and worker well-being in their production facilities [63], [64].

In cluster five, the keywords consist of "Industry 4.0," and "safety". As Industry 4.0 paves the way for the human-centric realm of Industry 5.0, collaborative robotics takes center stage. This paradigm shift prioritizes seamless human-robot collaboration, unlocking its potential to enhance both operator well-being and production efficiency while keeping costs in check [28], [65]. Industry 4.0's impact on workload depends on the chosen technologies and how workload is measured [66]. Lastly, the keywords in cluster six are "human factors," and "macro-ergonomics". Work can induce stress, especially due to issues with organizational structure and managerial quality [67], [68]. The Change Agent Infrastructure (CHAI) analysis uses interactive workshops with analysts and stakeholders to assess interventions driving concrete change within defined settings [69].

Active Country Analysis

This section discusses the contributions of countries in the domain of HFE research. Table 3 illustrates a quantitative analysis of countries actively involved in HFE research. The countries listed in Table 3 are based on the number of articles during the research period. According to the table, 20 out of 54 countries have a minimum contribution of 5 relevant articles, representing 80.45% of the total relevant articles. In terms of article quantity, the top five most productive countries are Italy, followed by Germany, the United States, India, and Canada. Italy also stands out as the most influential country based on the total research citations, with an average research publication year in 2021. Regarding average citations, Denmark leads among the 19 countries (39 times), followed by France (22 times) and Sweden (17 times).

Research in Italy is still predominantly focused on physical ergonomics (44.90%), followed by cognitive ergonomics (24.49%), a combination of physical and cognitive ergonomics (18.37%), and organizational ergonomics (12.24%). Research on physical ergonomics is also actively pursued in Germany (50%), the United States (52%), India (52.63%), and Canada (55.56%). Besides physical ergonomics, the United States has started actively publishing research on cognitive ergonomics (32%), while Germany and India focus on organizational ergonomics, with 26.92% and 21.05%, respectively.

Table 3. List of countries contributing to relevant articles

No.	Country	Number of articles	Total citation	Average citations	Average pub. year
1	Italy	49	790	16	2021
2	Germany	27	229	8	2021
3	United States	26	377	15	2021
4	India	19	127	7	2020
5	Canada	18	189	11	2021
6	Brazil	18	134	7	2020
7	China	18	104	6	2022
8	Iran	14	136	10	2020
9	Australia	12	99	8	2020
10	France	12	268	22	2020
11	Poland	10	44	4	2020
12	Sweden	10	166	17	2020
13	Indonesia	9	18	2	2020
14	United Kingdom	8	121	15	2021
15	Malaysia	7	28	4	2020
16	Denmark	6	200	33	2020
17	South Korea	6	53	9	2020
18	Colombia	5	42	8	2020
19	Portugal	5	25	5	2020
20	Turkey	5	32	6	2021

Article Analysis

The article analysis reveals the leading research within a research field and allows for a scientific understanding of the quantity and quality of references cited by other articles. This section focuses on generating the total citations from published research articles. Table 4 presents a summary of highly referenced articles related to HFE research. The top ten research articles listed in Table 4 are based on total citations during the period covered in this literature review. As shown in Table 4, the top three most-cited articles related to the HFE domain during this literature review period include Havard *et al.* [70] with 120 citations, Kadir and Broberg [1] with 112 citations, and Yu *et al.* [18] with 97 citations. Havard *et al.* [70] proposed an architecture involving real-time co-simulation, connecting digital twin and virtual reality environments. This co-simulation ensures realistic behavior in the physical system through digital twin simulation with an interaction interface facilitated by 3D representation in virtual reality. In this co-simulation, the scoring was assessed using the RULA approach.

Kadir and Broberg [1] presented empirical data from ten different industrial case studies conducted in ten different companies in the industrial sector in Denmark, related to factors that influence both positively and negatively the well-being and performance of the overall system. The results obtained indicate that during the introduction of new digital solutions, well-being and performance suffered. However, after successful implementation, there was an improvement in both well-being and performance.

Yu *et al.* [18] constructed a three-step approach to non-intrusively and automatically assess the physical fatigue of construction workers. The three-step method includes 3D motion analysis for worker movement data, kinetics, and kinematics to calculate joint torques, and fatigue modeling to determine capacity and fatigue index. The results showed that this approach has significant potential to enhance construction workers' understanding of physical fatigue in construction tasks. Managerial intervention is also required to organize tasks considering excessive workload.

Table 4. Summary of referenced published articles.

Authors	Year	Title	Total citation
Havard *et al.* [70]	2019	Digital twin and virtual reality: a co-simulation environment for design and assessment of industrial workstations	120
Kadir and Broberg [1]	2020	Human well-being and system performance in the transition to industry 4.0	112
Yu *et al.* [18]	2019	An automatic and non-invasive physical fatigue assessment method for construction workers	97
Mattsson *et al.* [71]	2020	Forming a cognitive automation strategy for Operator 4.0 in complex assembly	88
Jacobs *et al.* [72]	2019	Employee acceptance of wearable technology in the workplace	81
Kim *et al.* [73]	2019	Influences of augmented reality head-worn display type and user interface design on performance and usability in simulated warehouse order picking	79
Alabdulkarim *et al.* [74]	2019	Influences of different exoskeleton designs and tool mass on physical demands and performance in a simulated overhead drilling task	73
Kadir *et al.* [75]	2021	Human-centered design of work systems in the transition to Industry 4.0	67
Peruzzini *et al.* [76]	2019	A comparative study on computer-integrated set-ups to design human-centered manufacturing systems	64
Peternel *et al.* [16]	2019	A selective muscle fatigue management approach to ergonomic human-robot co-manipulation	63

Domain of HFE Analysis

The study grouped relevant research articles based on the scope of the discussed HFE domain. According to Table 5, physical ergonomics has been the most researched domain in HFE studies in the last five years. The total publications related to physical ergonomics are 171 articles or 48.44% of the total relevant research articles, followed by organizational ergonomics at 18.13%, and cognitive ergonomics at 15.30%. Regarding the combination of HFE domains, most studies focus on the combination of physical and cognitive ergonomics, accounting for 10.20% of 36 research articles, with the remaining on other combinations of HFE domains.

Table 5. List of HFE domains in relevant articles

No.	Domain of HFE	Total relevant articles	%
1	Physical	171	48.44%
2	Organizational	64	18.13%
3	Cognitive	54	15.30%
4	Physical & Cognitive	36	10.20%
5	Physical & Organizational	16	4.53%
6	Cognitive & Organizational	6	1.70%
7	All domains	6	1.70%

Figure 3 illustrates the research trend based on the HFE domain studied between 2019-2023. Referring to Figure 3, research related to physical ergonomics experienced an increase in 2019-2021 (50%-56%) and thereafter decreased until 2023 (43%). In contrast, research in cognitive ergonomics tends to be stable from year to year and the organizational ergonomics domain experienced an increase in 2022-2023. The physical ergonomics domain is still the dominant research domain in HFE despite its decline.

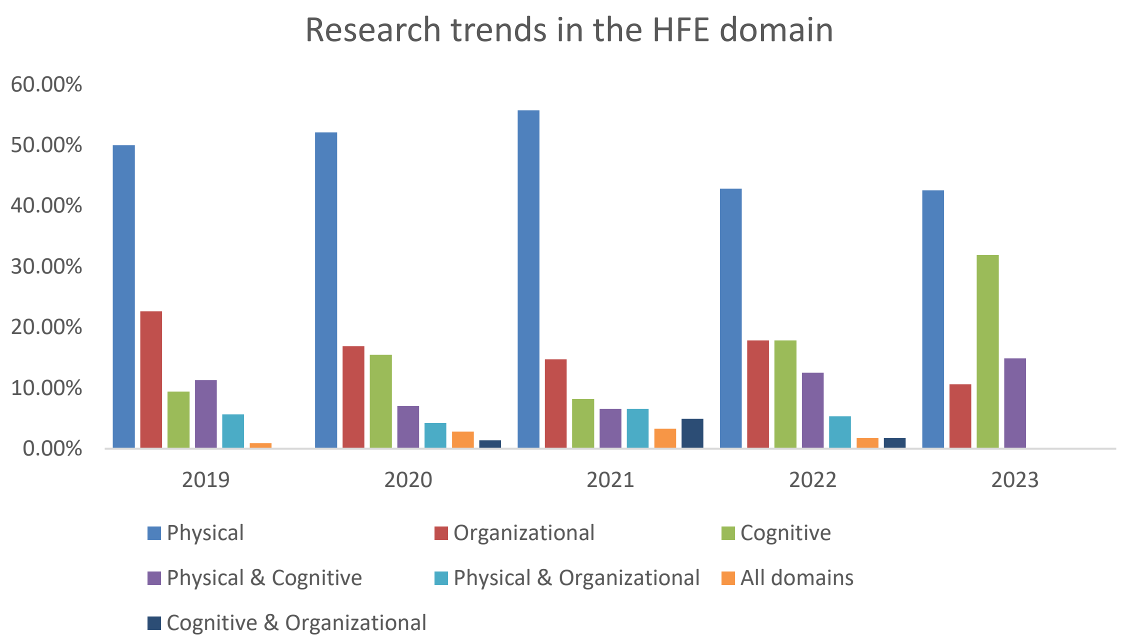

Figure 3. Research trends in the HFE domain

Discussion

In physical ergonomics, work-related musculoskeletal disorders (WMSDs) are prevalent concerns in various workplaces, with factors like prolonged awkward postures, repetitive movements, and excessive force playing significant roles. To address these issues effectively, ergonomic interventions have gained considerable research attention. This piece focuses on recent advancements in ergonomic evaluation tools and job rotation strategies for WMSD prevention.

Research related to ergonomic risk assessment and musculoskeletal disorders continues to be a focus in the domain of physical ergonomics. Disabilities related to pain indicate a connection with various risk factors, including lack of physical activity, body mass index, working hours, tenure, and ergonomic conditions for office workers [50]. The development of accurate WMSD risk assessment tools has been a key area of research. Examples include CERA, PRAMUD, DULA, DEBA, and well-established methods like RULA, REBA, OWAS, and NIOSH lifting equation [8], [12], [77], [78], [79], [80], [81]. Data collection, crucial for effective evaluation, utilizes self-reporting methods like interviews and questionnaires, often supplemented by observational techniques like video recording [82]. However, limitations like camera angles hindering accurate joint angle measurements necessitate the advancement of data collection hardware. Marker-based wearable sensors and tactile sensors with specific considerations for sensor dimensions, density, and accuracy are emerging as promising solutions. Notably, haptic feedback technology, informed by sensor data, holds the potential for significantly reducing unfavorable upper limb postures through targeted training. The efficacy of these tools has been demonstrated in ergonomic evaluations of collaborative robot workstations [83], [84], [85]. In addition to observation, ergonomic risk assessment can be conducted using machine learning. Machine learning methods used include Random Forest, Support Vector Machine, and Logistic Regression [17], [50].

Job rotation as a WMSD prevention strategy has gained traction in recent years. Research emphasizes its effectiveness in reducing ergonomic risks, highlighting the significance of biomechanical and organizational factors in designing optimal rotation schedules. While studies consistently acknowledge an increase in physical load exposure during rotation, appropriate strategies have been shown to positively influence overall exposure scores [86], [87], [88], [89]. However, Comper *et al.* [55] cautions against overemphasizing compliance, as strict adherence to rotation schedules may not necessarily translate to improved worker health or reduced exposure compared to more flexible approaches. Moreover, the perceived work exposure and prevalence of musculoskeletal symptoms may even increase with rigid schedules.

In cognitive ergonomics, measuring mental workload using NASA-TLX is a common topic of investigation [32], [90], [91]. Mental workload is also associated with employee status[31]. Heat stress is a discomfort factor affecting workers by reducing cognitive performance and mental workload [92]. Measuring mental fatigue levels can also be done using eye tracking, pupil size, and blink rate [21], [93].

Several studies of Virtual Reality (VR) indicated its potential to benefit both mental workload and task performance, with both significant and non-significant positive effects observed when compared to traditional methods. VR system studies in digital simulations consistently demonstrate reductions in task completion times, error rates, and perceived workload levels. Wang [94] emphasized that VR can have a redundancy effect on measurements, and participants are more compliant with alarms embedded through sound and technology-based methods, but there is no difference in evacuation effectiveness between them. Brunzini *et al.* [56] stated that in understanding operator workload to optimize VR training applications, it is necessary to consider mental demands during training, thus avoiding stress, excessive mental load, and improving user performance.

Human-centered design is based on user satisfaction, primarily related to performance, interaction, comfort, usability, accessibility, and visibility issues. However, real User Experience (UX) tends to be hidden and is usually challenging to detect. Grandi *et al.* [59] state that User Experience Index (UXI) can objectify UX validly and rapidly identify design optimizations in terms of accessibility, visibility, and performance. Combined evaluation of mental and physical workload can enhance the quality of assembly processes, revealing potential issues before physical implementation. Therefore, UXI can be a useful tool for providing rapid feedback during the design phase.

Participatory approach is a common approach in organizational ergonomics research. Stakeholder commitment is required to develop and implement ergonomic interventions within a valid framework [36]. Several key principles need to be emphasized, namely building relationships and shared commitment to gain a common orientation, using techniques or methods appropriate to organizational characteristics, and ensuring ease of management [61], [95], [96]. Variables such as working hours, job stability, occupational health, safety, team processes, technology, environment and task groups, knowledge, design requirements, communication, and information systems need to be considered [44], [97], [98], [99].

The advent of Industry 4.0, characterized by the pervasiveness of digital technologies within industrial settings, is inducing profound transformations in work systems. These transformations are expected to exert a multifaceted influence on both the operational efficacy of industrial systems and the well-being of individuals interacting with them. Notably, the impact of these new technologies on human well-being and system performance may exhibit dynamic variations across the distinct phases of pre-implementation, implementation, and post-implementation.

Kadir and Broberg [1] underscored the polymorphic nature of perceptions surrounding well-being and performance changes across these phases, encompassing both positive and negative viewpoints. Embracing Industry 4.0 represents an organizational metamorphosis, demanding a holistic perspective that acknowledges its multifaceted impact on both human and technological components. This transformation necessitates the involvement of diverse stakeholders, including internal decision-makers at various levels (strategic, tactical, operational), as well as external consultants specializing in ergonomics and human factors/ergonomics (HF/E). In general, research in physical ergonomics has entered the era of industrial revolution 4.0. This is characterized by several studies involving big data and machine learning. However, the amount of research is still very small. Current research is conducted more on digitalization and information technology (revolution 3.0). For example, in analyzing the level of ergonomic risk, researchers use a computer connected to other digitalization tools. Likewise, this also applies to cognitive and organizational ergonomics.

The field of Human Factors and Ergonomics (HFE), particularly in cognitive and organizational ergonomics, appears to have yet to fully embrace the principles of Industry 4.0. The integration of technologies such as the Internet of Things (IoT) and machine learning remains relatively underutilized. For instance, current methods for assessing mental workload often rely on computerized techniques, necessitating controlled environments for accurate assessment. To bridge this gap and adapt to Industry 4.0, HFE research can explore the application of machine learning to automate the measurement of workers' mental workload and associated risks.

Therefore, future research should first prioritize the development of real-time ML models or artificial intelligence related to these topics, whether for physical, cognitive, or organizational ergonomics research. Second, while the bulk of Virtual Reality (VR) research demonstrates positive effects on mental workload and task performance, further investigation is needed to refine its application in big data analysis. The previously proposed protocol should be implemented on a larger sample of inexperienced operators to provide a more comprehensive assessment of its efficacy. Subsequent research should then focus on defining specific metrics for evaluating the training effectiveness in this population, such as time to completion, error rates, and cognitive strain indicators. Finally, this study highlights the need for greater emphasis on organizational ergonomics research. This will offer valuable insights into workplace design, employee well-being, and overall organizational productivity.

Conclusion

This review study uses science mapping and literature analysis related to research trends in the scope of Human Factors and Ergonomics (HFE), including physical ergonomics, cognitive ergonomics, and organizational ergonomics, in the field of engineering studies. There are four steps used in this research, including literature search, literature selection, science mapping analysis, and qualitative discussions to explore emerging research gaps. The four-step methodology is used to identify and determine the current position of HFE research in the era of the Industrial Revolution. Current HFE research remains predominantly rooted in the Industrial Revolution 3.0 era. Some studies have begun to transition into the Industrial Revolution 4.0 era by leveraging machine learning, particularly in physical and cognitive ergonomics. There is still a significant need for advanced HFE research that necessitates the utilization of machine learning or artificial intelligence (AI) to align with the widespread advancements of Industry 4.0.

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